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We have conducted a study of "smart walls" which combines micro-electro-mechanical sensors and actuators with a neural network controller in a single layer of silicon for active flow control. We have determined the optimum arrangement of sensors and actuators for a single neural network controller under the influence of noise. With sensors and actuator implemented in hardware and the neural network simulated by computer, wind-tunnel experiments have demonstrated that the control unit is capable of controlling TS waves and wave packets. The experimental results are in good agreement with our previous numerical simulations of the control process. Using DNS for realistic actuator configurations, we have developed an efficient procedure to provide training data for the network controller. In preparation for a smart wall with multiple control units, we have developed DNS-based techniques to analyze the flow response to multiple actuator movements.

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1 Introduction

The goal of the smart wall project is to improve aircraft fuel efficiency by decreasing the skin friction drag on aircraft surfaces. Our smart wall seeks to maintain the inherently low friction characteristics of laminar flow by delaying transition to turbulence. Earlier numerical simulations (AIAA-93-3273) showed great promise in the smart wall concept. Further experimental work under the parent award validated claims that the smart wall is capable of delaying transition to turbulence on a flat plate (Fan *et al.* 1994, Fan 1995). Additional research has been concerned with efficient design procedures for single flow control units and optimum array arrangements toward the hardware implementation of the smart wall.

2 Objectives

A detailed description of the research objectives is given in the parent awards, AFOSR-91-02-62 and F49620-93-1-0135. In general, the work performed under AASERT has been aimed at harmonizing the details in the smart wall concept. The objectives are as follows:

1. Investigate hardware considerations.
2. Analyze spacing of sensors and actuator for optimal control effect.
3. Evaluate flow response to actuator motion via numerical simulations.
4. Improve control mechanism through numerical simulations.
5. Implement smart wall control unit in hardware.

Individuals supported under AASERT were involved in all objectives.

3 Achievements

We have shown that properly trained neural networks can establish the complex nonlinear relationships between multiple inputs and outputs which are characteristic of an active flow control system. We have introduced an active laminar flow control method which delays transition to turbulence. Our

smart wall is based on the wave superposition principle and aims at the cancellation of TS instability waves and wave packets. We have documented computational and experimental evidence which establishes the smart wall as an emerging engineering concept for turbulence drag reduction.

The promising results from numerical simulations led to experimental validation. A single control unit implemented in hardware has successfully canceled artificially generated TS waves and wave packets. The efforts have been continued to prepare for the implementation of the smart wall in hardware. The following subsections detail achievements.

3.1 Hardware Considerations

The smart wall controller must be made robust to defective manufacture or damage during use. The distributed information in neural networks makes them innately tolerant to faults. However, in some training instances, portions of the network architecture become too influential in the control process. If any of these portions of the network architecture were to be damaged, the network controller would fail to return appropriate control signals. The goal in network fault tolerance is not to allow any portion of the network to be too influential, such that its removal would be catastrophic. These concerns were addressed in our design of a pre-trained fault tolerant neural network (Hofmann, 1993, M.S. Thesis). Similar fault tolerant networks have been documented by Neti, Schneider & Young (1992) and Simon & El-Sherief (1993). Our work improves the training procedure for fault-tolerant networks.

Additional concerns such as generalization capabilities (network ability to return proper output from untrained input) and network accuracy must be considered. In fact, smaller networks have better generalization capabilities, while larger networks are more accurate. We concluded that the smallest network with sufficient accuracy that is trained for fault tolerance results in the optimal network trade-off between accuracy, generalization capabilities and fault tolerance. Similar conclusions were drawn by Hammerstrom (1993) and Bartlett & Uhrig (1992).

3.2 Spacing of Sensors and Actuators

Our first model of a flow control unit has two upstream sensors (input to the neural network controller), one actuator (wave cancellation mechanism),

and a downstream sensor (feedback to the controller). The spacing of these components greatly affects the ability of the control unit to cancel instability waves. When sensors are too close, noise deteriorates the effectiveness of the control. Sensors which are too far apart fail to properly determine the characteristics of the incoming waves. Our research demonstrates that the optimal upstream sensor spacing is $1/4$ disturbance wavelength. The distance between sensors and actuator is larger to prevent interference of the upstream effect of the actuator. The feedback sensor should be about one wavelength downstream of the actuator to allow for the decay of transients in the flow response.

A more recent model of the control unit employs only one upstream sensor and time-delayed signals to the neural network. Current numerical simulations of this control unit show great promise.

3.3 Control Unit for Wind-Tunnel Experiments

Our transition control experiments are performed in a low turbulence, closed return, low-speed wind tunnel. The test section is $0.6m$ wide by $1.2m$ high and $5.95m$ long. A vertical aluminum plate, $5.4m$ long, is positioned $5cm$ from the back wall of the test section. The control unit is situated $1.72m$ downstream of the leading edge. The disturbance generator is located $0.5m$ upstream of the control unit. The hot wire, located $0.36m$ downstream of the control unit, is used to measure the wave residual. The experiments are performed at $U_{\infty} = 12.7$ m/s. Typically, a sinusoidal wave at $73Hz$, a frequency close to the most unstable TS wave, is used to drive the disturbance generator either continuously or for single cycles to produce wave packets.

One of the major tasks in preparing the experiment has been the replacement of an outdated Microvax with a PC-based data acquisition and control system that interfaces to the SGI workstations used for numerical simulations. The neural network for hardware control is simulated on a high speed DSP-based special purpose computer board with its own A/D and D/A front end for real time control. Since this board is only programmable in C, the data acquisition software (previously in Fortran) had to be rewritten. All software for operating the hardware is now written in C, as the neural network software. Matlab was installed in both the PC and the SGI computers for easier setup (e.g. of the traverse movement) and data analysis.

The two sensor signals for the control unit are provided by the signal

differences (to eliminate common low-frequency fluctuations) of three microphones with flat frequency response. These small signals are very noisy. Instead of attempting to reduce the noise, we directed our efforts to improve the network controller to cope with this more realistic situation. The disturbance generator consists of a latex membrane spanned over a 2.54 cm diameter hole, the actuator of a similar membrane over a 2.54 by 12.7 cm slot. Both membranes are driven by loudspeakers through power amplifiers that are connected to either a function generator or the D/As of the PC board.

The software used for numerical simulations of network training and operation was ported to the PC board with one minor change: a fixed phase shift of the output (actuator) signal had to be applied to compensate for the larger spacing between sensors and actuator in the experiment. The network training was successfully performed with the noisy sensor signals. In recall mode, the basic control unit applied in the wind tunnel experiments successfully attenuated artificially generated wave trains and wave packets. A marked control effect is evident such that the flow downstream of the control unit is either laminar with control, or turbulent without.

The encouraging results suggested further improvements of the neural network controller to adapt to changing flow situations, to plan for the implementation of multiple control units, and to explore the feasibility of building control units in silicon.

3.4 Actuator Flow Response

Each control unit contains a single downstream actuator. This actuator acts in accord with an upstream and downstream sensor and a neural network controller to cancel instability waves and wave packets. The actuator used in experimental procedures is a rectangular hole (long side in spanwise direction) spanned by a latex membrane which is actuated by a pressure differential. The motion of the membrane directly affects the streamwise and normal component of the velocity near the wall. The detail how, and how quickly, this motion causes counter waves is important for the layout of adaptive control units, especially the positioning of feedback sensors, and the ultimate array arrangement of control units for a smart wall. In addition, the upstream influence from the actuator on the sensors might affect sensor readings transmitted to the network controller.

A multigrid DNS code developed by Liu *et al.* [1993] has been modified to accept boundary conditions which emulate actuator movement at the wall, with the actuator deflections given in Berker (1963). The laminar flow regime, where smart walls are envisioned, inherently supports the principle of superposition for instability wave cancellation. As the DNS code is computationally expensive, Duhamel's Superposition Integral (Hildebrand, 1990) is employed to model the flow response to changing actuator movements and amplitudes. DNS output is used in numerical simulations of the smart wall to provide accurate flow quantities at specified locations.

A sinusoidal excitation of the actuator has been chosen to compare DNS results with measurements of the flow response in the wind tunnel. Availability of the DNS results has permitted the evaluation of approximate techniques to measure the membrane deflection and to clarify the asymmetry of the flow over the actuator in the center plane. With corrected procedures, experimental data and DNS results are in good agreement. A membrane deflection of 0.05 mm is sufficient to introduce a TS wave of 1% of the free-stream velocity two TS wavelengths downstream of the center of the actuator. The excitation of TS waves with the membrane avoids the long transients observed in vibrating-ribbon experiments. Within 1.5 TS wavelengths, the disturbance profile is indistinguishable from the theoretical profile.

To gain flexibility in studying different actuator excitations and ultimately to numerically analyze the complete control process, we have developed a DNS-based approach using Duhamel's superposition integral. A first run starts slightly upstream of the disturbance generator and considers a ramp-like rise of the generator membrane over a small number n of time steps. The membrane remains in this raised position for the duration of the run. The second, smaller run starts slightly upstream of the first sensor and considers a ramp-like rise of the actuator membrane over n time steps. In both runs, only small fractions of the solution are saved every n time steps along the whole span, e.g. the pressure at the sensor positions and the streamwise velocity at the hot-wire position.

So far, the Duhamel technique has been applied to smaller domains for which the data base can be obtained with workstations. At a fixed spanwise station, the run provides a single time series that can be integrated to obtain the combined receptivity and disturbance growth for the full range of unstable 2D and 3D TS waves in agreement with the predictions of the linear stability theory. Outside the unstable range, only a small forced response remains.

Judging from our results so far, the technique is very powerful and may be useful beyond our immediate interest.

3.5 Effect on Flow Control Units

The concept of the Duhamel integration has not only enabled to quickly simulate the flow response to actuator motions, but also suggested the new model of the control unit that works with a single input sensor and time-delayed signals. The fast simulations of the flow response provide accurate data for the on-the-fly training of the adaptive control unit developed by X. Fan (Fan 1995). Availability of realistic training data assisted in significant improvements to the flow control unit. Computational experience obtained with the new model greatly enhanced our confidence in the smart wall potential in wind tunnel experiments.

3.6 Experiments with the New Control Unit

Our new model of a control unit has been applied in the low speed, low turbulence wind tunnel and successfully canceled artificially generated wave trains and wave packets. Control was highly effective such that the flow downstream of the control unit was either laminar with control, or turbulent without. The current control unit can adapt to changing flow situations and effectively delay transition to turbulence. For the first time in the field of laminar flow control, truly adaptive feedback control has been achieved for both continuous TS waves and periodically occurring wave packets in realistic experimental situations.

4 Future Work

Results have demonstrated the smart wall capable of two-dimensional instability wave cancellation for delay of transition to turbulence. However, boundary layers on aircraft surfaces are inherently three-dimensional. Future research will investigate smart wall delay of transition to turbulence on a swept-wing. The preparations for these investigations require optimization of the array arrangement of control units. Our development of the fast simulation of the flow response to actuator arrays will be an enabling technique

in these studies.

5 Personnel

The following personnel were partly supported under this contract:

Lorenz M. Hofmann, Graduate Student (earlier M.S., now Ph.D. level)

Matthew Avery, Graduate Student (M.S. level) Fall 1993 until Summer 1994.

Robert Briggs, Graduate Student (M.S. level). Since Winter 1994.

L. Hofmann earned the Master of Science Degree from the Department of Mechanical Engineering at The Ohio State University in December 1993 thanks to support from AASERT. He began work towards the Ph.D. degree in Mechanical Engineering in January 1994. His main topic is the use and improvement of the DNS code for developing the Duhamel technique toward a design tool for flow control systems.

Matt Avery began work towards a Master's degree in Aeronautical and Astronautical Engineering in June 1993. He worked with J. Haritonidis on the wind tunnel, wrote the C software, and integrated the computer components with the experimental equipment. In Summer 1994, he decided to pursue other avenues, leaving the experimental program in limbo.

Robert Briggs, who holds a B.S. in Aeronautical and Astronautical Engineering and worked for some years at Morton Thiokol, Utah, is a new member of our team since Winter 1994. He has concentrated on multi-grid methods to modify/rewrite the DNS code for three-dimensional boundary layers.

All personnel involved in the work under this and the parent award attended weekly research meetings to jointly focus on the project goals.

6 Papers, Presentations, and Theses

The following publications, presentations, and theses acknowledge the support of AASERT:

"Active Flow Control with Neural Networks," by X. Fan, L. Hofmann, and Th. Herbert, *AIAA 3rd Shear Flow Conference*, Orlando, Florida, July 1993. AIAA Paper No. 93-3273 (1993).

"Neural Networks for Active Flow Control," by X. Fan, L. Hofmann, and Th. Herbert, *46th Meeting of the American Physical Society, Division of Fluid Dynamics*, Albuquerque, New Mexico, November 21 - 23, 1993. *Bull. Amer. Phys. Soc.*, Vol. 38, pp. 2251-2252 (1993).

"Transition Control Using Neural Networks," by J. H. Haritonidis, M. Avery, X. Fan, and Th. Herbert, *46th Meeting of the American Physical Society, Division of Fluid Dynamics*, Albuquerque, New Mexico, November 21 - 23, 1993. *Bull. Amer. Phys. Soc.*, Vol. 38, p. 2251 (1993).

L. Hofmann, "Neural Network Design for Fault Tolerance," M.S. Thesis, Department of Mechanical Engineering, The Ohio State University, 1993.

"The Flow Field Associated with Wave Cancellation," by J. H. Haritonidis, L. Hofmann, and Th. Herbert, *47th Meeting of the American Physical Society, Division of Fluid Dynamics*, Atlanta, Georgia, November 20 - 22, 1994. *Bull. Amer. Phys. Soc.*, Vol. 39, p. 1979 (1994)

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